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SECURITY CLASSIFICATION OF THIS PAGE

(2)

AD-A205 082

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release;
Distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR-TR- 89-0095

6a. NAME OF PERFORMING ORGANIZATION
Colorado State University

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
AFOSR/NC

6c. ADDRESS (City, State, and ZIP Code)
Engineering Research Center
Room B305
Fort Collins, CO 80523

7b. ADDRESS (City, State, and ZIP Code)
Building 410
Bolling AFB, DC 20332-6448

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
AFOSR

8b. OFFICE SYMBOL (If applicable)
NC

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
F49620-86-C-0080

8c. ADDRESS (City, State, and ZIP Code)
Building 410
Bolling AFB, D.C. 20332-6448

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61102F	2310	A1	

11. TITLE (Include Security Classification)
Mesoscale Severe Weather Development Under Orographic Influences. Final Report. (Unclassified)

12. PERSONAL AUTHOR(S)
Elmar R. Reiter, John D. Sheaffer and Marjorie A. Klitch

13a. TYPE OF REPORT
Final Technical

13b. TIME COVERED
FROM 7/1/86 TO 9/30/88

14. DATE OF REPORT (Year, Month, Day)
1989 January

15. PAGE COUNT
24

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Mesoscale Weather Systems; Severe Weather Forecasting; Numerical Modeling; Surface Energy Budgets

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Measurements of surface energy budgets have been carried out at several sites in the Colorado Rocky Mountains, in the Kansas Prairie, in the Gobi Desert and in Tibet. The fluxes of sensible heat, H_S, from the surface could be estimated as functions of the difference between air temperature and infrared "skin surface" temperature, as seen by remote sensing instruments. Computations of H_S involve a neutral stability coefficient for turbulent transfer (drag coefficient), C_T, ranging between 0.0021 (Gobi Desert) and 0.0070 (alpine tundra), and a scaling factor for stability. Latent heat fluxes were estimated either as residual of total energy fluxes or through a Bowen ratio approach.

These flux estimates worked well in a mesoscale, nested-grid model over the Rocky Mountains. The model was able to predict with considerable skill flash-flood events such as the Big Thompson flood of 1976 and the Cheyenne flood of 1985.

By implanting "features" such as a vorticity maximum associated with a low-level jet stream, the model without the nested grid was able to predict severe cyclogenesis ("bomb" formation) over the eastern United States. Both model versions run on a desktop workstation.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
Lt. Col. James G. Stobie

22b. TELEPHONE (Include Area Code)
(202)767-4960

22c. OFFICE SYMBOL
NC

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCALSSIFIED

AFOSR-TR- 89-0095

MESOSCALE SEVERE WEATHER DEVELOPMENT UNDER OROGRAPHIC INFLUENCES

Final Report To
U.S. Air Force Office of Scientific Research
Grant No. F49620-86-C-0080

Work Conducted between 1 July 1986 and
30 September 1988

by

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January 1989

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MESOSCALE SEVERE WEATHER DEVELOPMENT UNDER OROGRAPHIC INFLUENCES

1. OVERVIEW.

This report summarizes research efforts conducted during the two-year period from 5-1-1986 to 9-30-1988 under Grant AFOSR-F49620-86-C-0080.

The original tasks under this grant were as follows:

(1) A study of the role of topography in the development of mesoscale convective systems (MCS) during summer over, and downwind of, the Rocky Mountains and the Tibetan Plateau.

(2) Assessment of orographic effects on rapid, severe weather developments during seasons other than summer (such as lee cyclogenesis, heavy precipitation, blizzard conditions, high winds, etc.).

Many of our research results have already been reported in the open literature and at scientific conferences. In the following summary our research efforts are grouped into three main topics: (1) Surface energy fluxes in mountainous terrain; (2) Development of a numerical prediction model sensitive to detailed topography; and (3) Modeling of severe winter storm conditions.

2. MEASUREMENT OF SURFACE ENERGY FLUXES IN MOUNTAINOUS TERRAIN

2.1 Introduction

The development of simplified parameterizations for surface energy transformations and the assessment of their regional scale variability over real surfaces are significant problems of current interest for improved representations of diverse terrain and weather conditions in numerical models. We have recently made extensive observations of the surface energy budgets at several sites in the Colorado Rockies (Reiter et al., 1987a), on the Tibetan Plateau (Reiter et al., 1987b), and in the First ISLSCP Field Experiment (FIFE) study area near Manhattan, Kansas. These data contain continuous energy balance observations for extended periods over a wide range of surface cover, terrain and climatological conditions. Initial work with these data yielded a simplified procedure for estimating the stability dependence of turbulent fluxes of sensible heat at the surface (Sheaffer and Reiter, 1987) and offered a general method for relatively simple parameterizations for vertical heat and momentum fluxes over vegetated surfaces. Several of our data sets also include simultaneous energy balance observations for as many as four sites and, hence, contain basic information on the regional, or "sub-grid" scale variability of surface fluxes in mountainous terrain.

Our research centered on the analysis of energy budget measurements at 14 highland sites in Colorado and on the Tibetan Plateau. Specific initiatives included the analysis and parameterization of the following:

(1) "Sub-grid" variability of stability dependent fluxes over highly variable terrain. Simultaneous energy balance measurements for multiple mountain peak and valley sites over spatial scales ranging up to 200 km were used to assess the nature and effects of sub-grid variability in relation to grid-averaged representations typically employed in numerical models.

(2) The main effects of vegetation cover on surface energy exchange processes. We used our data base to refine and validate a generalized model of the surface energy balance wherein vegetation is accommodated as a simple, textured layer superimposed on the soil. The combined effects of mechanical roughness and the effective surface or "leaf area" for exchange of heat and moisture are represented as a single stability dependent exchange parameter.

2.2 Methods of Analysis

The choice of instrumentation used in our field measurement programs has been dictated mainly by constraints of continuous operation for extended periods, in an unattended mode, in remote and often hostile environments. In addition to the lack of external power to drive the systems, sandstorms (in the Gobi) and summertime snow- and hailstorms (in Tibet and the Rocky Mountains) precluded the use of sensitive, but fragile thermocouples, sonic anemometers and fast response humidity monitors. Even with these concerns, some of the equipment used in our Tibet experiment succumbed to unexpected, rough handling by local helpers in the course of shipping. The current configuration of our surface energy budget station is depicted in Fig. 1, and Table 1 provides a complete listing of the instrumentation.

Although data from either 10 or 20 meter meteorological towers, wherever deployed, gave information on mean vertical profiles of wind, temperature and humidity, the time constraints of the sensors were inadequate for resolving high frequency variations sufficiently to allow meaningful eddy correlation measurements. Also, standard flux/profile similarity approaches to estimating fluxes from tower profiles are inappropriate in view of the highly advective conditions at most sites. These constraints required that alternative methods of analysis be developed to obtain reasonable estimates for continuous values of the complete energy budgets from the instruments in Table 1. In addition to simply characterizing the flux properties of various surfaces, our objectives included acquiring sufficient information to allow the development of reliable parameterizations of varying surface conditions in complex terrain.

Our analyses and data comparisons have therefore relied mainly on data from the radiation stations which included meteorological observations on relatively short, 3-meter towers. The radiative components of the surface energy budget are measured directly by upward and downward pointing radiometer arrays. Heat storage in the soil, vegetation and surface litter are estimated from the time variation of soil temperature and moisture, with estimates of the soil heat capacity and conductivity. Recently added soil heat flux plates (Table 1) greatly improved the reliability of this part of the analysis. Whereas most studies of land surface heat fluxes ignore the thermal inertia of vegetation, we have found it to be significant for rapidly changing conditions. The residual difference between net radiation and surface/subsurface heat storage is considered to be the energy available to the atmosphere which can be decomposed into latent and sensible components. Sheaffer and Reiter (1987) (see also Reiter et al., 1987b; Smith et al., 1986) developed a bulk aerodynamic procedure for estimating the turbulent flux of sensible heat using these data, with the remaining energy then being the latent flux.

This bulk aerodynamic procedure for estimating sensible heat fluxes employs the mean difference between air temperature at three meters above the surface and the infrared temperature (IRT) of the surface, derived from measurements of upwelling terrestrial infrared radiation, as the primary parameter governing surface layer flux. The significant innovation in the development of this procedure was the derivation of stability dependent scaling functions based exclusively on this temperature difference (Sheaffer and Reiter, 1987). These functions are the

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equivalent of integrated forms of flux-profile functions derived by Paulson (1970). However, our functions are based directly on observations of bulk differences rather than tower profile data, and hence are appreciably simpler and potentially more reliable for analyses in complex terrain.

The bulk aerodynamic formula for estimating surface layer fluxes of sensible heat (H_s) is given by Eq. 1.

$$H_s = \rho C_p U_a C_T (T_a - IRT) \tag{1}$$

Terms on the right side of Eq. (1) include a neutral stability coefficient for turbulent transfer, C_T, air density, ρ; wind speed, U_a; the difference between air temperature, T_a, and IRT; a stability scaling factor,

$$\psi = (1 - a.Ri)^b,$$

where Ri is a bulk Richardson number based on (T_a - IRT), and a and b are empirical constants.

The use of IRT in Eq. (1) as the lower level temperature for both the layer temperature gradient and for the bulk Richardson number avoids the introduction of additional empirical factors to estimate a low-level air temperature near the surface. This intermediate step is normally done so that established stability scaling functions derived from profile data (Dyer and Hicks, 1970; Dyer, 1974), can be employed. Figure 2 shows a comparative analysis of air temperature differences between 0.5 and 2.5 meters above the surfaced and differences between IRT and air temperature at 2.5 m. These data are for a tall grass prairie near Manhattan, Kansas.

In Fig. 3, values of C_T, derived by inverting Eq. (1) with sensible heat flux measurements for the same data as in Fig. 2, are shown as a function of the local bulk Richardson number. The flux values for this analysis were estimated by applying a local Bowen ratio measurement to decompose the residual flux difference between measured values of net radiation and soil heat storage. For the unstable case ($Ri < 0$), ψ was defined as $(1-10.Ri)^{0.5}$. Because of lingering uncertainties regarding the best representation for stable-case values of the scaling function, values were set equal to unity at points to the right of $Ri = 0$ in Fig. 3. In general, we have found that flux values for the stable case can be effectively scaled with a function of the form

$$\psi = 1.0-4.0(Ri/(1.0+5Ri)).$$

The analysis in Fig. 3 shows stability normalized values for C_T of approximately 0.009 but with appreciable scatter for near neutral conditions where small errors for both H_s and (T_a-IRT) introduce large relative uncertainties into the calculation. The unscaled, stable case data in Fig. 18 also reveal appreciable scatter, but decrease slowly toward a small, nonzero value near Ri values of approximately +0.2. This same analysis approach for data taken over a sand and pebble surface in the Gobi desert yielded C_T values of 0.0026, and values of 0.0024 and 0.0035 for sites at Nagqu and Lhasa, Tibet, respectively. Other typical values obtained for C_T include 0.0021 to 0.0024 for snow cover and 0.0030 to 0.0070 for various Alpine grass and tundra sites in the Rocky Mountains.

These, and similar results for other sites, suggest that the stability scaling function, as defined above, seems to provide a fairly reliable representation of buoyancy effects for the unstable case. Additional studies of selected data under unstable conditions should also be useful and a thorough examination of our FIFE data should yield additional information for the stable case. The same procedures

have also been inverted to obtain similar estimates of other energy-transfer related values including surface wetness parameters.

Our surface *IRT* values are obtained from high quality hemispheric pyrgeometers (see Table 1). These values represent the vertically and horizontally averaged temperature of that portion of the vegetation cover which is directly involved in turbulent energy exchange with the atmosphere. Hence, a mean condition inclusive of wet/dry, exposed/shaded and transpiring/desiccated plant tissue is surveyed. Whereas stability dependent values of ψ simply scale C_T for buoyancy effects, C_T must then implicitly accommodate ventilation of the vegetation layer, as well as surface roughness, in generating mechanical turbulence. Because of this ventilation effect, values derived for C_T must, in part, reflect the magnitude of the effective surface area involved in surface heat (or moisture) exchange. This argument is consistent with our observation that, all other factors being equal, values obtained for C_T are primarily a function of the density or "leaf area" of surface vegetation. Additional work with these data will decompose C_T for various surfaces into separate components for mechanical roughness and for foliage surface area, the latter also including a wetness factor which adjusts for evaporating dew or rainfall.

We have adopted the view that, in general, vegetation cover can be represented as a textured, heat exchanger-like layer of transpiring material superimposed on the soil surface. A translucent property can be added for areas with relatively thin vegetation, and various canopy factors can be added where appropriate. Specification of the precise location of the "surface" as characterized by *IRT* values (or by an equivalent parameter for surface humidity) still is somewhat arbitrary. However, some physical realism can be introduced by defining a simple conductivity expression for the flux of heat and moisture through the base of the vegetation layer, between the *IRT* "surface" and the top of the soil. Note that this representation avoids the introduction of parameters to estimate leaf area, wind speed within the foliage layer, and specific empirical exchange coefficients for the foliage elements. The bulk representation also employs the simple difference between the actual surface (skin) conditions which can be measured reliably by remote sensing, and a single set of near-surface meteorological parameters. Hence, potential errors related to hypothetical equilibrium conditions at the surface, assumed in the derivation of profile based exchange functions, are minimized.

Error estimates in using *IRT* data for computing turbulent energy fluxes involve the accuracy of the radiometric instrumentation and the emissivity of the surface. As noted in Table 1, the long wave radiation monitors used in our energy budget stations are rated as accurate within one percent. Whereas an equivalent black body surface will be a perfect emitter, the actual temperatures of imperfect emitters, i.e., realistic surfaces, are somewhat warmer than IRT values obtained, assuming an emissivity of 1.0. We have studied these problems by examining values of (T_a-*IRT*) for situations during which this difference should be small (i.e., overcast nocturnal conditions with very strong winds) while iteratively varying the effects of possible instrument and emissivity errors. Instrumental errors of approximately 0.5 percent have been identified in this way. The estimated emissivity values derived in these studies are consistently 0.985 or greater, with the exception of the Gobi Desert, where a value of approximately 0.96 was observed.

2.3 Results

The main intent of our research program was to measure the components entering into local surface energy budgets in complex terrain, and to determine if such fluxes could be parameterized effectively in numerical models, using variables which might eventually be determined for large areas by remote sensing techniques.

Studies to date have emphasized the acquisition of reliable energy budget data from remote, poorly documented mountainous areas of the western United States. Initially, the rationale for making point measurements in these areas which have drastic variations of terrain and surface cover over short distances was simply that having some measurements was better than having none at all. As noted above, we have overcome some of the problems of representativeness by deploying multiple stations to define the range of conditions occurring in some areas. Strategies have included simultaneous measurements for peaks and adjacent valleys and for similar settings on several peaks in larger regions. The refinements of our monitoring instrumentation and of our analysis procedures have also been ongoing processes.

In the Rocky Mountains we have also been able to tie some of the nocturnal high-wind events observed at mountain peaks to the evaporation of rain falling into the subcloud layer of thunderstorms over the Continental Divide. We have been able to track some of these outflow events through our station network. This outflow tends to occur in relatively thin sheets of air, but covers distances much larger than those usually associated with squalls over the plains.

A summary of our monitoring programs is given in Table 2. We started out during the winter, spring and summer, 1984 to test several radiation and surface energy budget instrument configurations for their suitability in complex terrain by deploying them in the mountains west of Fort Collins, CO and on the peak of Mt. Werner near Steamboat Springs, CO. These measurements gave first evidence of diurnal wind systems at mountaintop level which have eluded standard, ill-placed and ill-timed radiosonde data (Reiter et al., 1987a). This circulation appears to be a characteristic property of the summertime boundary layer over mountainous areas with important implications for the spatial redistribution of heat and moisture as well as for feedback processes governing the surface flux budgets. In spring and summer of the same year, surface energy budget measurements were carried out by us, in collaboration with the Lanzhou Institute for Plateau Atmospheric Physics, Lanzhou, PRC, in the Gobi Desert along the northern edge of the Tibetan Plateau (Smith et al., 1986).

During the summer of 1985 we instrumented 20 mountain peaks in western Colorado and northern New Mexico with automated wind, temperature and humidity measuring equipment. At four locations, surface radiation and soil heat and moisture fluxes were measured simultaneously for complete energy budget assessments. This Rocky Mountain Peaks Experiment (ROMPEX-85) was conducted in collaboration with the Los Alamos National Laboratory and with the U.S. Forest Service (Reiter et al., 1987a), mainly to see if the diurnal wind systems encountered on Mt. Werner in 1984 could be observed again, and to estimate their areal extent.

In summer of 1986 two surface energy budget stations were operated in Tibet (Reiter et al., 1987b). In the summer of the same year, the Mt. Werner energy budget station was reactivated to obtain more data on the interannual variability of monsoonal and nonmonsoonal weather systems and their effects on the diurnal wind systems. In summer of 1987 additional mountain peak and valley stations were established between the Continental Divide and Mt. Werner to gain some insight into the interaction between regional energy budgets and the wind systems in the PBL. During spring and summer of 1987 we also participated in FIFE (First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment) in complex terrain near Manhattan, Kansas.

Finally, during the summer of 1988 we operated an energy budget system plus three automated weather stations in a valley near Grand Junction, Colorado to examine the local flux budget in relation to airflow in three adjacent tributary valleys.

At the same time, we again operated two flux monitoring systems in a ridge/valley configuration at our Mt. Werner site for a period of three months.

Three recent journal articles (Reiter et al., 1987a,b; Sheaffer and Reiter, 1987) describe details of two field programs and subsequent analyses. The emphasis in the discussion presented here centers on relatively recent results. More extended discussions of these analyses are forthcoming in the open literature (Bossert et al., 1989).

Surface energy budgets at four sites were studied as part of our ROMPEX-85 program. The settings for three of these stations, namely Mt. Werner, Vail and Flat Tops, were quite similar on well exposed, essentially treeless peaks. The fourth station (Crested Butte) was in a large clearing, just off the local peak, with good westerly exposure. Recently, we have directed our attention to details of the temporal covariation of heat fluxes at these four sites which were scattered over a 200 by 200 km area. Of interest is the extent to which significant differences occur over this spatial scale as a function of regional weather and by time of day. Although this work is still in progress, the important findings can be briefly summarized.

Differences in energy fluxes between the four ROMPEX-85 sites are generally rather small, reflecting mostly the effects of local conditions. It is the local variations of surface layer stability which characterize differential feedback and hence, the actual rates of energy fluxes to and from the atmosphere in complex terrain. Therefore, useful comparisons between these sites may be made in terms of the time variation of local stability factors governing turbulent exchange as expressed by the diurnal cycle of the bulk Richardson number at each site.

Averaged surface layer stability data for late August 1985 (Fig.4) represent a period dominated by regional high pressure and very dry conditions throughout the area. Diurnal cycles of stability for three of the sites are quite similar, both in terms of amplitude and in the details of time variations. The elevations of all four sites are essentially equal. However, significantly higher peaks and ridges near the Crested Butte site cause this location to be enveloped in a valley circulation at night with notably weaker winds and hence, much stronger stability values.

An interesting feature of the stability cycles at the other three sites (Mt. Werner, Vail, and Flat Tops) is the tendency for near neutral conditions to occur in association with intermittent easterly winds beginning several hours after sunset. These periodic surges, typically of several hours duration, appear to be associated with large inter-basin transfers of accumulating cold, stable air. It should be emphasized that these surges are distinct from the more powerful, convectively driven winds described by Reiter et al. (1987a) and Sheaffer and Reiter (1987) in that they are weaker, less persistent and occur in the absence of moist convective processes. The significant feature in Fig. 4 is that the effects of these nocturnal oscillations appear to some degree at all three mountaintop stations, indicating a fairly widespread phenomenon. The somewhat different aspects of the diurnal cycle at Flat Tops is in part the result of localized eddying caused by a vertical, 300 meter cliff just east of the site.

In Figs. 5 and 6, diurnal cycles of the Richardson number are shown for the summit of Mt. Werner and for the adjacent valley (Brunner Draw). These stations are separated by 950 meters of elevation and 10 km of lateral displacement. The two sets of curves represent contrasting conditions of strong synoptic flow (Fig. 5) and weak flow (Fig. 6). In each case appreciably stronger stability conditions persist at the valley site.

3 MESOSCALE NUMERICAL PREDICTION MODEL

3.1 Model Development.

Our studies of severe mesoscale weather over mountainous terrain necessitated the development of a numerical model which could portray most of the physical processes involved in such weather patterns and, at the same time, could take into account details of the underlying terrain as one of the forcing factors for mesoscale weather systems. We departed from a model originally described by Anthes and Warner (1978). Considerable modifications were introduced to allow such a model to run efficiently on a desktop workstation. The original model applications were over Tibet and China (Shen et al., 1986a). New vertical data interpolation schemes were introduced which permitted the efficient use of observed winds, temperatures and geopotential heights from radiosonde observations (Shen et al., 1986b).

Over Tibet and China the model could rely only on mandatory-level data, because significant point data were not released by the Chinese. In spite of these shortcomings in the database, the model performed well in predicting vortex development over, and to the east of, the Tibetan Plateau giving rise to severe precipitation events. Sensitivity studies were conducted to asses the effects of certain physical processes, especially those involving sensible heating, on the development of such vortices (Shen et al., 1986c).

3.2 Model Refinement.

In a major research effort, leading to a Ph.D. dissertation (Tucker, 1988), the model originally developed by Shen, Reiter and Bresch was refined to include a nested-grid capability with higher resolution of terrain features. In the design of the nested-grid model version we departed from the customary approach which carries out all the predictive time integrations on the fine grid. Such an approach necessitates decreases in the integration time steps commensurate to the higher resolution of the space scale by the nested grid. Thus, a four-fold decrease in grid distance, say, from 96 km to 24 km, causes a penalty factor of 64 in computer runtime. Since our model was designed to run on a desktop workstation, such a penalty was deemed unacceptable. Furthermore, matching the predictions on the fine grid, where a lot more integration time steps are involved, with those on the larger grid often leaves imbalances.

Our approach (Tucker and Reiter, 1989a) uses the nested grid with 24 km horizontal resolution only to assess the influence of detailed topography on the wind fields of the lowest two sigma-levels of the model. These effects are calculated under neglect of advective terms, as those would require changes in the integration time steps. The model in its present form can run with 3-minute integration time steps on the 96-km grid as well as on the 24-km grid, thereby realizing a factor of 64 in runtime savings, and avoiding most of the mismatch problems between the two grids. The adjustments in the wind fields, necessitated by topography, are propagated to adjustments in the mass divergence and vorticity fields, which affect the moisture balance. Through a Kuo-type parameterization, precipitation is calculated on the fine grid. Release of latent heat affects the temperature distribution on the fine grid as well.

The small adjustments in the affected fields are averaged into the grid point locations of the 96-km grid, where the next 3-minute time integration is performed as a first guess for the subsequent adjustment step on the fine grid. Thus, both grids are fully interactive throughout the model calculations.

3.3 Model Verification.

The model has yielded excellent predictive results in several cases of severe weather development over the United States. Several of the cases under study were concerned with convective precipitation during summer in the Rocky Mountain regions, such as the infamous Big Thompson Flood of July 31, 1976, which killed 135 people, and the Cheyenne Flood of August 1, 1985 with 12 victims.

Because observations of precipitation depend on a rather spotty rain gauge network, it was deemed necessary to use skill analysis techniques which are capable of pattern recognition, rather than relying on measures of root-mean-squared errors. Such techniques are offered by the multivariate, randomized block permutation techniques (Tucker et al., 1989).

Applying these techniques to the nested grid model predictions of severe precipitation cases, a significant level of forecast skill was revealed. The fact, that this model runs on a desktop workstation holds promise for eventual applications in distributed weather prediction (Koermer, 1987).

3.4 Sensitivity Studies.

Having a mesoscale prediction model which performs well with severe precipitation events allows the user to play "what-if" games. We have conducted a number of sensitivity studies (Tucker and Reiter, 1989b) to assess the relative importance of synoptic weather patterns, topography, moisture distribution and diabatic processes on the development of conditions that lead to flash-flooding events in the Rocky Mountains. From these studies it appears, that events which, on the surface, may appear similar, often differ drastically in their causes.

4. MODELING OF SEVERE WINTER STORMS.

4.1 Scientific Accomplishments

The focus of research was directed toward rapid storm development, or cyclogenesis, during winter months. The approach to the research involved analyses of explosively deepening midlatitude cyclones, or "bombs", which occur over land, in order to determine the key signatures of bomb development. The work was divided into two separate tasks:

1. A comprehensive diagnostic effort aimed at examining the nature of explosive cyclogenesis, including a comparison of bombs and nonexplosive, or regular, cyclones. The generation of vorticity, divergence, and latent heating patterns during the incipient, explosive, and mature phases of bombs were analyzed and compared to similar phases of regular cyclones (Macdonald and Reiter, 1988).

2. A numerical modeling effort of the bombs and regular cyclones using the same cases studied as in the diagnostic effort. A "feature" component was developed and incorporated into a existing numerical model in order to improve the prediction of central sea level pressure in a bomb. The model was also used to examine the sensitivity of cyclogenesis to slight adjustments in the input data fields, and it was used to calculate the trajectories of air parcels which were deemed to be important to explosive cyclogenesis.

Details of this work are largely covered in the dissertation prepared under this grant by Bruce C. Macdonald (1988).

4.1.1 Diagnostic Studies

Although bombs are more a marine than a continental phenomenon, there are a number of reported cases of bomb development over the eastern United States. Bombs are associated with strong surface winds, heavy precipitation, and rapidly changing weather conditions, and therefore are a major concern to operational weather forecasting. The research described below focused on continental bombs over the United States in order to find the crucial signatures which distinguish bomb development from the development of regular cyclones.

A total of seven bombs were identified during a six-year period. The bombs developed and reached their mature phases over the eastern United States, with the position of most explosive deepening generally over the central Mississippi Valley. One of the bomb cases involved the infamous Ohio blizzard of January 1978, in which the central sea level pressure reached 957 mb, with a 24-hour pressure drop of 40 mb. Twelve cases of regular cyclones were also examined. The regular cyclones moved across the eastern United States, with their intermediate phases occurring over the central Mississippi Valley. Analyses were prepared on a grid with 72 km resolution centered over the Mississippi Valley and using data interpolated from radiosonde soundings at every 50-mb level. The primitive equations, rewritten in terms of a vorticity tendency equation, a divergence tendency equation, and a thermodynamic equation were used to study the dynamics of explosive cyclogenesis. Three separate phases were identified for bombs: the incipient phase, the explosive phase and the mature phase. Each succeeding phase followed the previous phase by 12 hours. The regular cyclones were also divided into three phases, each separated by 12 hours: the incipient phase, the intermediate phase, and the mature phased.

Composite analyses of vorticity, vorticity tendency, divergence and latent heating were performed for each phase of both the bombs and the regular cyclones. Both vertical profiles and horizontal or spatial composites were prepared. Each case was also analyzed in detail in order to determine the nature of critical signatures of development which might not show up on the composite analyses.

In many ways, both the diagnostic and modeling studies show that bombs are more intense versions of regular cyclones. There is a strong convergence in the lower troposphere around the center of a bomb, there is an intense core of upward vertical motion with a great deal of latent heating, and there is a pattern of strong divergence aloft. Bombs appear to be driven more by "dry" processes in their early stages, but appear to be more dependent on latent heating for their final development into the most intense phase. Bombs develop along strong baroclinic zones and require a configuration of physical components similar to that in regular cyclones to bring about development. These components include vorticity advection in the upper troposphere, a conditionally unstable atmosphere, and a strong source of moisture. This research has focused on finding the distinct characteristics, or signatures, of bombs which may provide a key to both the understanding and prediction of bomb development. While one should obviously take careful note of the differences between bombs and regular cyclones, one should not lose sight of the fact that there are fundamental physical similarities between the two types of storms.

A series of vertical profiles over the surface position of the storm center was developed for each phase of each of the two classes of storms. The profiles revealed several important signatures of bomb development.

1. The vertical profile of vorticity in a bomb shows a rapid increase of vorticity in all layers of the troposphere as the storm progresses from its incipient through its explosive and mature phases. The greatest increases occur in the lower troposphere, especially below 700 mb. During all phases of bomb development, the relative maximum in vorticity remains in the lower troposphere, near 850 mb, with a relative minimum in the upper troposphere. In regular cyclones, the vorticity increases only slightly in the lower troposphere, with little difference in the middle and upper troposphere as the storms mature.

2. The vertical profile retains a distinctive vertical gradient of vorticity in the incipient and explosive phases. This gradient weakens somewhat during the mature phase. Regular cyclones also show relatively high vorticity values in the lower layers, but the vertical profile is dramatically different from that associated with a bomb. Relative vorticity values are nearly constant with height in the regular cyclones.

3. The vorticity tendency equation shows that the lower tropospheric increases result mainly from the convergence term for both the bombs and the regular cyclones, but this term is stronger throughout a deep lower-tropospheric layer for the bombs. Upper-tropospheric vorticity is dominated by the advective terms and a nearly off-setting influence of the divergence term for both classes of storms. The magnitudes of these two terms are considerably stronger for the bombs than for the regular cyclones.

4. In the incipient and mature phases of a bomb, the lower layer of convergence is very deep, extending to 600 mb, and the upper layer of divergence is also very deep, indicating that there is a well-defined layer of nondivergence around 500 mb. As the bomb reaches a mature stage, this pattern weakens and tends to be confined to more shallow layers. The regular cyclones show a similar, but considerably weaker, vertical profile of convergence and divergence with an ill-defined layer of nondivergence.

5, During the most explosive growth phase of bomb development, the vorticity and geopotential (wind and mass) fields tend to remain largely in balance, with a slight imbalance promoting convergence in the lowest layers and divergence at jet stream levels. Estimates of total divergence tendency, without consideration of the frictional effects, show an indication for convergence at all levels. In regular cyclones the vorticity and mass fields are slightly out of balance at all tropospheric levels, tending to promote convergence at all levels.

6. Total latent heating tends to be much stronger for bombs than for regular cyclones, at all comparable phases of development.

7. Convective latent heating in bombs is strongest during the incipient phase and weakens during each of the later phases. The maximum heating occurs in the 600- to 750-mb layer for all phases.

8. Large scale latent heating in bombs is strong during all phases, but is most intense during the explosive phase. There appears to be a tendency for the level of maximum large scale heating to shift downward as the storm progresses from its incipient to its mature phase. During the explosive and mature phases, the large scale heating is clearly stronger than the convective component.

9. Convective latent heating in regular cyclones shows very little change from phase to phase, with a slight maximum during the intermediate phase. Large scale latent heating in regular cyclones tends to increase slightly from the incipient to the

mature phase, with the level of maximum heating shifting from 500 mb to around 750 mb during the same time period.

10. Convection is strongest in the area to the south and southeast of the storm center during the three phases of a bomb, but the large scale heating is well focused over the center of the storm, especially during the explosive and mature phases. Regular cyclones show a much more diffuse pattern of heating than the bombs.

11. Both bombs and regular cyclones show an increase in moisture content in the lower troposphere as the storms grow from the incipient to the mature phases. The bombs are considerably more moist than the regular cyclones at comparable phases, especially during the explosive and mature phases.

12. There appears to be little change in the static stability of a bomb during its three phases. This factor indicates that the tendency of a storm to shift to smaller scales, thus becoming more intense as the storm destabilizes, is not evident in the data.

13. The intrusion of stratospheric air into the storm core appears to be a very weak factor in generating vorticity, even at upper levels. The generation of vorticity in bombs, by this factor, is similar to that in the regular cyclones.

14. A distinct signature of a developing bomb appears to be evident in the upper half of the lower troposphere, between 850 and 600 mb. In this layer the convergence, vorticity, and generation of vorticity by convergence are especially strong for the bombs and are weak in the regular cyclones. There is generally a maximum in latent heating in this layer as well.

On a case-by-case basis there appear to be several important aspects of bombs in comparison to regular cyclones.

1. The upper level vorticity maxima, at 500 mb and 250 mb, appear to be nearly in phase with one another for the bombs, but in regular cyclones, the 250-mb maximum passes over the storm center ahead of the 500-mb maximum.

2. In the warm sector, to the east and southeast of a developing bomb, there appears to be a strong vorticity maximum associated with a relatively high moisture content and a strong moisture gradient in the lower troposphere from 950 to 800 mb. In regular cyclones, this maximum is weaker and the moisture content and gradients are less than those observed with the bombs. The vorticity maximum appears to be related to the existence of a low-level jet in the warm sector ahead of the storm. The identification of this jet streak and an estimation of its maximum winds or vorticity appear to be crucial components of predicting the development of a bomb.

4.1.2 Numerical Modeling Efforts.

A numerical model was applied to test the importance of several key components of cyclogenesis. A mesoscale "feature" is expressed mathematically and is used to capture the mutual adjustments in the geopotential, or temperature, fields and the wind fields. This feature allows the cyclones to intensify to a greater extent than in the nonfeature model, and it provides a more realistic prediction of central sea-level pressure for the bombs. For the regular cyclones, the feature model is able to predict the intensity of storms which intensify slightly, but if a storm weakens notably, the feature model erroneously maintains the strength of the storm.

The feature model generates realistic vorticity and divergence profiles for the bombs, correctly depicting the depth of the convergence and divergence layers and

correctly predicting an increase in vorticity at all levels of a developing bomb. The vertical profiles of vorticity are predicted rather well also.

The model's ability to capture the relationship between the precipitation, or latent heating patterns, and the storm center appears to be a crucial factor in predicting cyclone intensification. If the model predicts precipitation which is too intense near the center of the storm, the forecast central sea-level pressure will be too low. If the model's precipitation pattern is well removed from the storm center, the central sea-level pressure will be too high.

The model was used to generate trajectories of parcels of air which are initially located in the warm sector of an incipient storm. The results shows that parcels of air which have high relative vorticity and which have high moisture content and are associated with strong moisture gradients tend to be drawn into a bomb. In the regular cyclone cases, the parcels with similar but weaker characteristics, usually are not drawn into the storm. It is evident that the ambient vorticity and moisture fields, and their relationship to one another, play an important role in generating a bomb.

The model was used to test the relative importance of the vorticity and moisture fields in causing explosive cyclogenesis. A series of experiments was developed to provide smoothed or adjusted wind, height and moisture fields for input into the model. The results show that the decrease in vorticity by smoothing at upper levels has only a marginal effect on cyclogenesis. The upper-level vorticity advection and divergence are important components of bomb formation, but they do not appear to be limiting components.

A smoothed lower-level vorticity field also has a slight impact on cyclogenesis. As the vorticity maxima are reduced, the predicted central sea-level pressures will increase. An experiment in which the moisture gradient was shifted away from the predicted storm track indicated that the lower-level moisture is crucial in predicting storm intensification. The moisture content in the lower troposphere, and its position relative to the lower-layer vorticity pattern, appear to be the most important components of explosive cyclogenesis. A separate experiment in which the lower-layer moisture field was merely smoothed provided little change in the prediction of storm intensity.

These diagnostic and modeling studies provide a broad view of the nature of explosive growth of storms located over continents and along polar fronts, generally during the winter months. It will be important to extend these efforts to include a larger sample of storms. Comparable analyses should be conducted for a separate population of bombs within polar air streams, and a separate analysis of explosive growth over the oceans. Perhaps the most important characteristics described here involve the nature of the intensification in the lower tropospheric layers of the storms, particularly between 850 mb and 600 mb. In addition, the importance of the ambient fields of vorticity and moisture in the lower layers, not immediately associated with an incipient storm, needs to be addressed in greater detail. The identification of a low-level jet streak in the warm sector appears to be a critical component of predicting explosive cyclogenesis. Numerical models will provide a valuable tool for investigating bomb growth, and the development of specific model components, such as "features", needs to be investigated more extensively.

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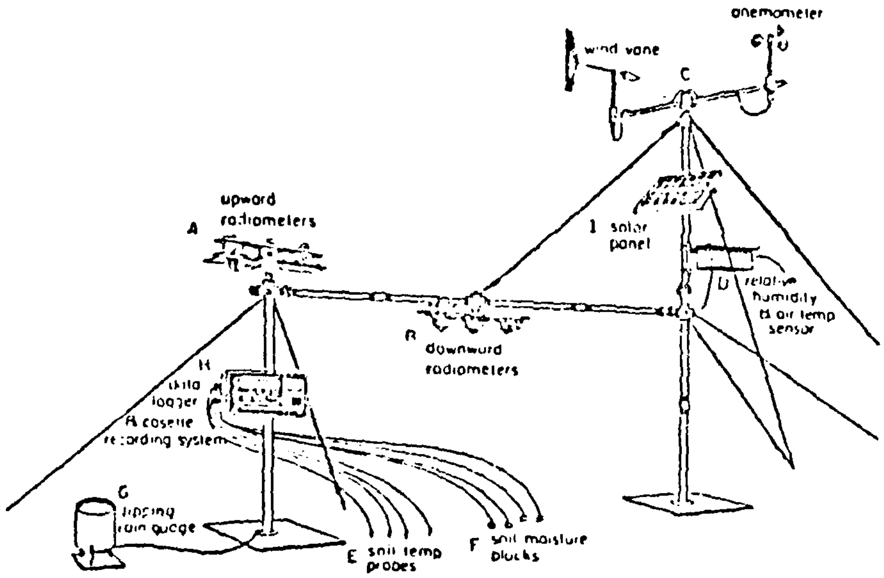

Figure 1. Schematic illustration of the radiation station. Bowen ratio module, soil heat plates, and barometer are not shown. Air temperature and humidity sensors are normally situated just below the wind sensors.

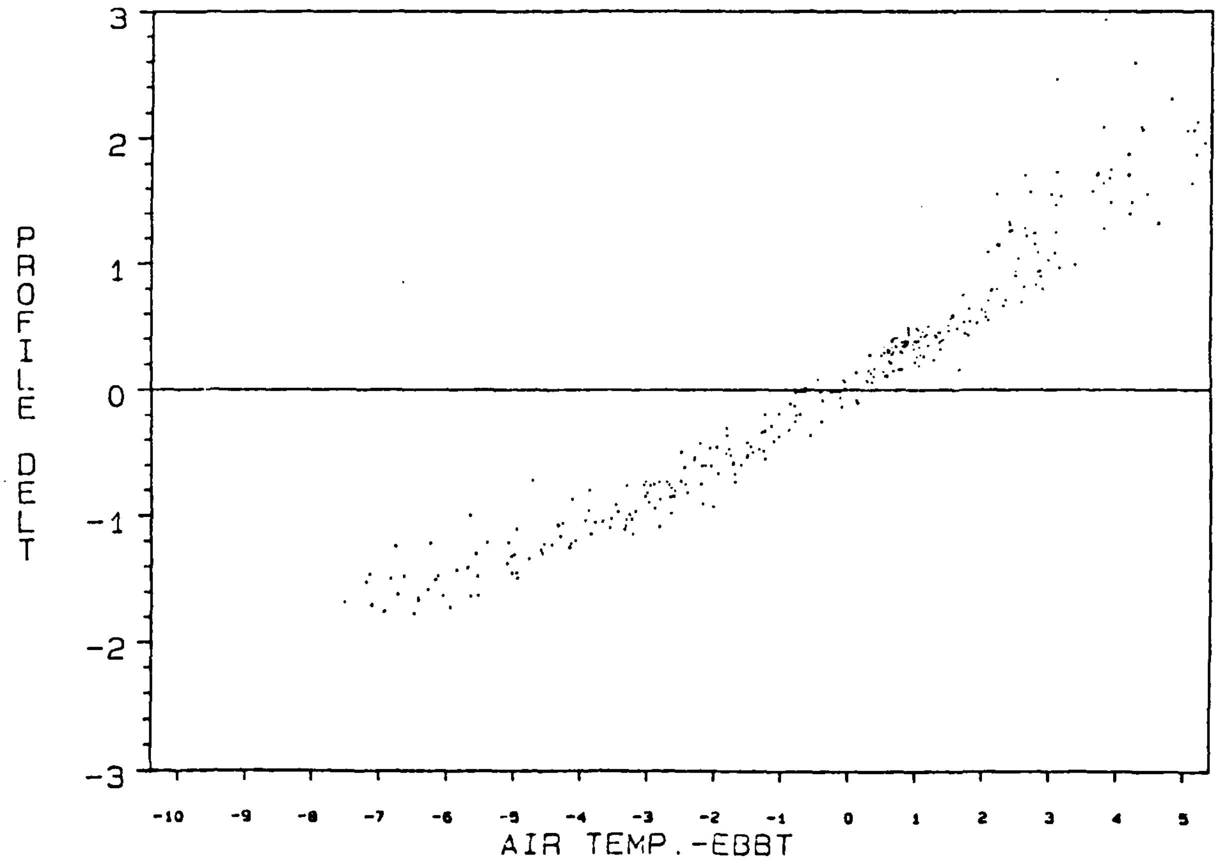

Figure 2. Analysis of air temperature difference (DELT) between 0.5 and 2.5 meters above the surface, versus the difference between the effective black body temperature (EBBT) of the surface and air temperature at 2.5 meters over a tall grass prairie near Manhattan, Kansas for Oct. 6-16, 1987.

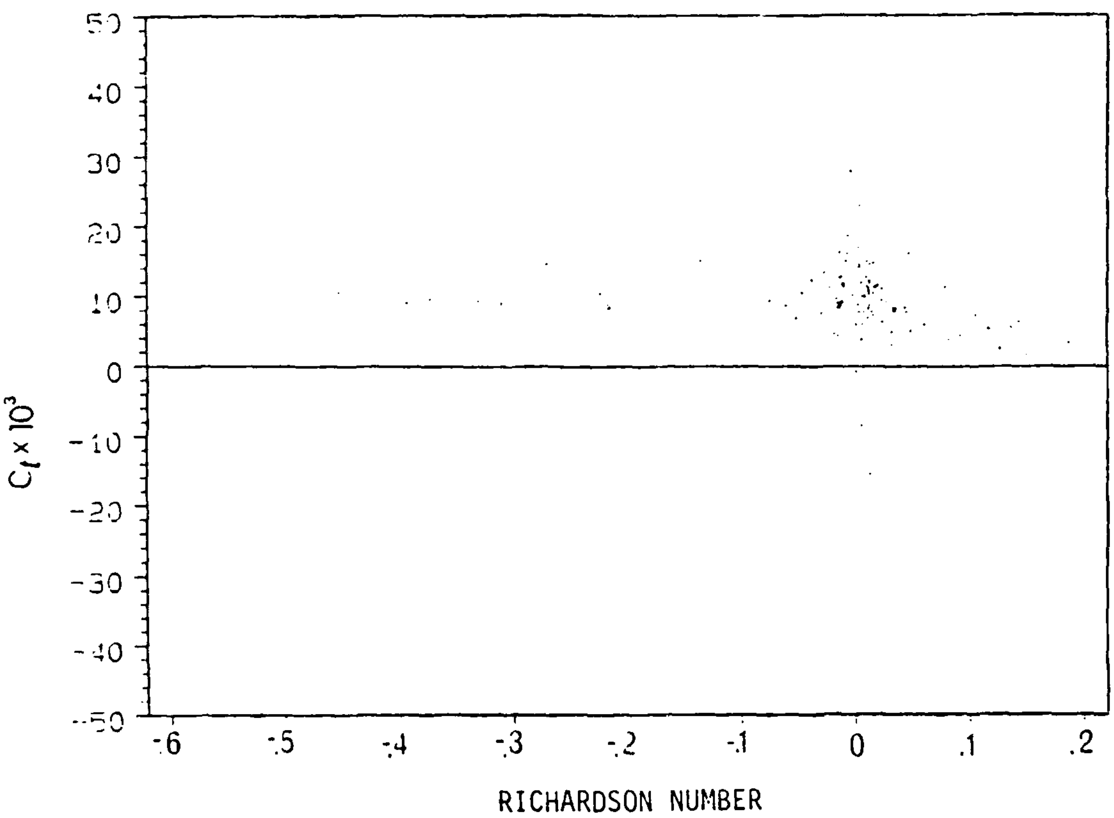

Figure 3. Plot of C_T, or $[\frac{H_s}{\phi \rho C_p U_a (T_a - IRT)}]$ versus Richardson number, normalized for stability for the unstable case only. Values of C_T for the stable case (Ri>0) are not adjusted for increasing stability and hence represent the product $C_T \phi$.

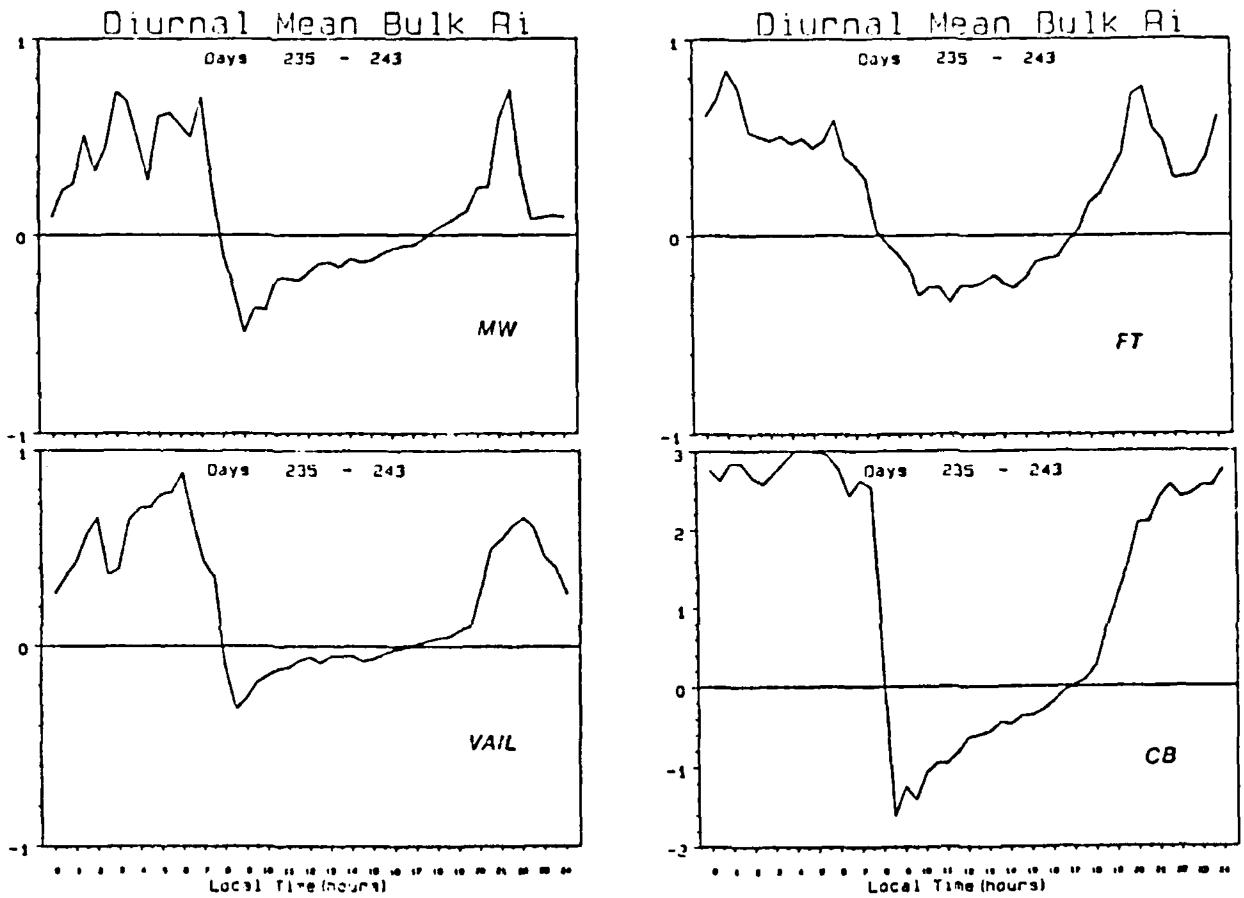

Figure 4. Diurnal cycles of average bulk Richardson number at four ROMPEX 85 stations for Aug. 23-31, 1985. The site designations are Mt. Werner (MW), Vail (V), Flat Tops (FT), and Crested Butte (CB).

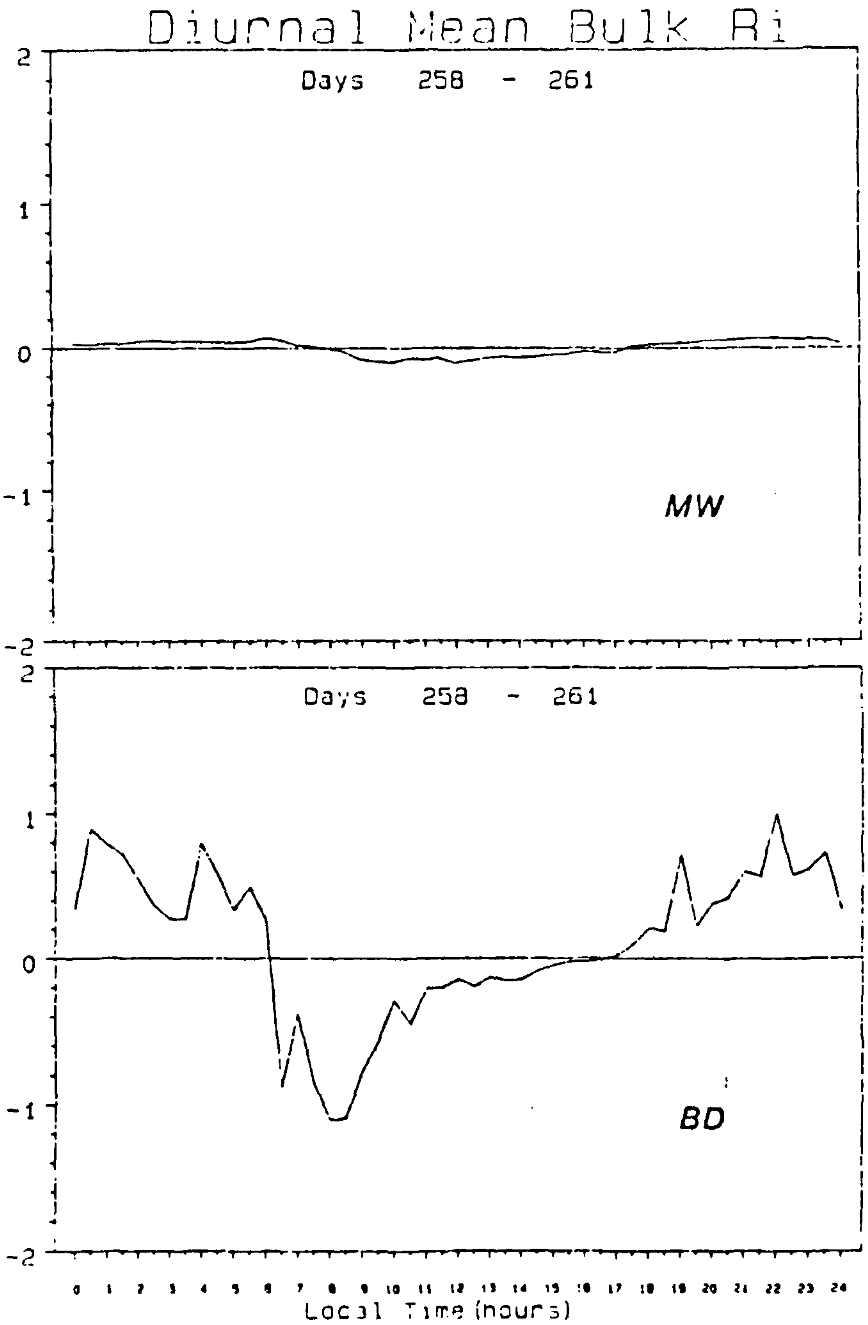

Figure 5. Average diurnal cycle of bulk Richardson number at Mt. Werner (MW) and at Brunner Draw (BD) for Sept. 15-18, 1987.

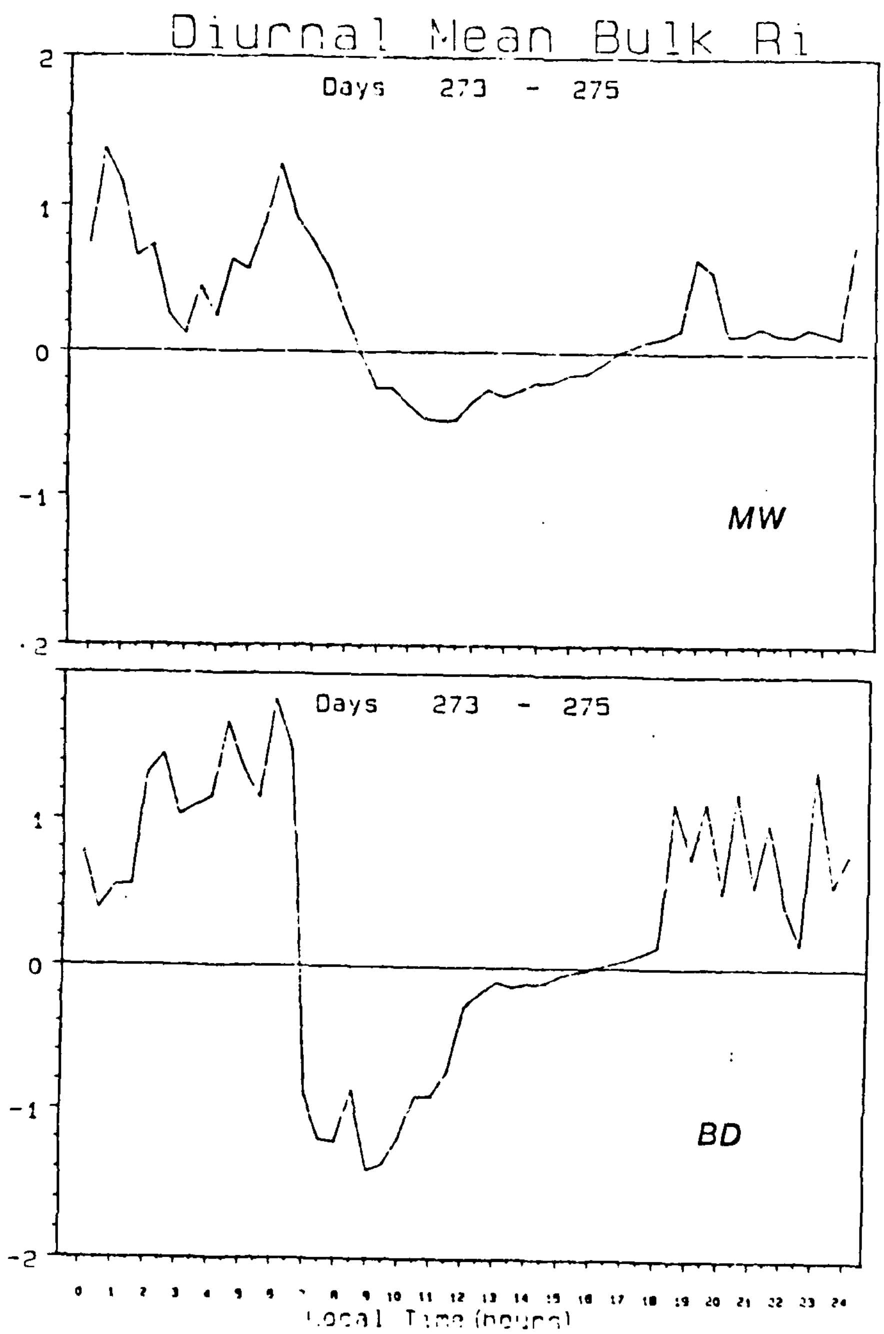

Figure 6. As in Fig. 5, but for Sept. 30 to Oct. 3, 1987.

Table 1: Instrumentation

Instrument	Comments
Radiation Station	
Two Eppley precision spectral pyranometers with quartz (W6-295) inner and outer hemispheres	Measuring 0.2- to 4.0-μm solar radiation ($\pm 1\%$)
Two Eppley precision spectral pyranometers with colored glass (R68-Schott) outer hemispheres	Measuring 0.7- to 4.0-μm solar radiation ($\pm 1\%$)
Two Eppley precision infrared pyrgeometers with silicon hemispheres and sink-dome thermistors	Measuring 2.0- to 50.0-μm terrestrial radiation ($\pm 1\%$)
Campbell Scientific (CSI) cup anemometer and wind vane (model 014A and 024A)	Measuring wind speed and direction 3 m above surface (± 0.25 m s^{-1}, $\pm 5°$)
CSI 207 thermistor and hygristor	3m ($\pm 0.2°C$, 5% relative humidity)
Four CSI 107 soil thermistors at 0.02-, 0.08-, 0.20-, and 0.40-m depth	Soil temperature measurements ($\pm 0.2°C$)
Two sets of CSI Fritschen soil heat plates*	Reliability varies with soil type
Four CSI CEL-WFD-7 ceramic soil moisture blocks at the same level as temperature sensors	Reliability varies with age and soil type
CSI R62501 tipping rain gauge	1.0-mm sensitivity
CSI CR-7 data logger	Computes 15-min average values from 5-s scan intervals and records maximum and minimum values and average data on magnetic tape
CSI Bowen Ration System*	Air temperature and humidity at 0.5- and 2.0-m (0.01°C for air temp. and 0.05°C for dew point)
Tower Station	
R.M. Young 27005J-Goll U.V.W. propeller anemometers at 2, 4, and 8 m	Accuracy varies with angle of attack, cosine corrections required
CSI 207 thermistors and hygristors at 0.25, 2, 4, and 8 m	($\pm 0.2°$, $\pm 5\%$ relative humidity)
CSI CR-7 data logger	Computes 5-min average values, correlation statistics, variances, etc., from 2-s scan interval data and records all parameters on magnetic tape

The manufacturer specifications for the accuracy of each instrument are shown in parenthesis.

*Added in May 1987.

Table 2. Summary of Energy Budget Monitoring Experiments

Site	Dates	Comments
Pingree Park, CO*	Mar-July, 1984	Mountain valley
Gobi Desert*	Apr-July, 1984	Highland desert
Mt. Werner, CO*	July-Oct, 1984	Mountaintop, alpine tundra
ROMPEX-85	July-Sept, 1985	Four Colorado mountaintop sites, grassy tundra
Fort Collins, CO*	Feb-May, 1986	Native high plains grassland
TIPMEX-86*	June-July 1986	Two Tibetan sites, wet valley meadow and highland plains grassland
ROMPEX-86	July-Oct, 1986	One (Colo.) alpine tundra site
ROMPEX-87	June-Oct, 1987	Two (Colo.) sites, alpine tundra and valley meadow
FIFE-87**	May-Oct, 1987	Two tall grass prairie sites, ridge and valley

*Signifies that both radiation stations and micrometeorological towers were deployed at these locations.

**Signifies that heat flux plates and Bowen ratio modules were added.

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John D. Sheaffer, Research Associate
Ru Jin Shen, Visiting Chinese Scientist

ADVANCED DEGREES AWARDE

Ph.D. Awarded to Donna Frances Tucker, 2 October 1987.
Dissertation title: "The Anatomy of Heavy Rainfall Episodes Over Complex Terrain: A Modeling Approach"